FCV Learning Demonstration: Factors Affecting Fuel Cell Degradation

Jennifer Kurtz, Keith Wipke, Sam Sprik

Fuel Cell Durability & Performance
Miami, Florida
November 15, 2007

This presentation does not contain any proprietary or confidential information

Contents

Fuel Cell Vehicle Learning Demonstration

- ***Objectives***
  - Validate H_2 FC Vehicles and Infrastructure in Parallel
  - Identify Current Status and Evolution of the Technology
    - Assess Progress Toward Technology Readiness
    - Provide Feedback to H_2 Research and Development

Key Targets

Performance Measure	2009*	2015**
Fuel Cell Stack Durability	2000 hours	5000 hours
Vehicle Range	250+ miles	300+ miles
Hydrogen Cost at Station	$3/gge	$2-3/gge

* To verify progress toward 2015 targets
** Subsequent projects to validate 2015 targets

Hydrogen refueling station, Chino, CA Photo: NREL

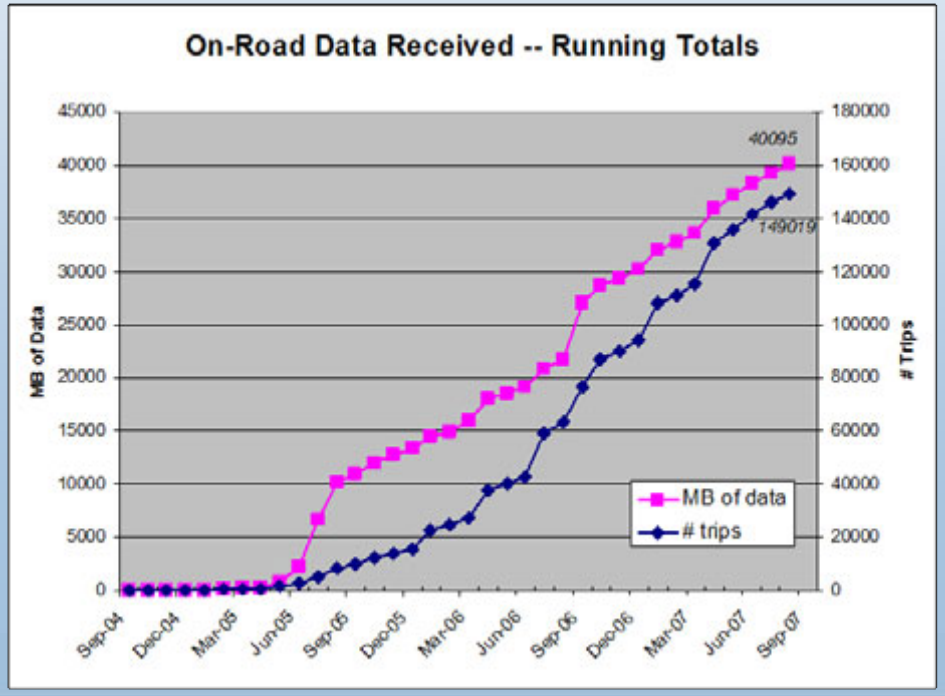
Learning Demonstration Partners

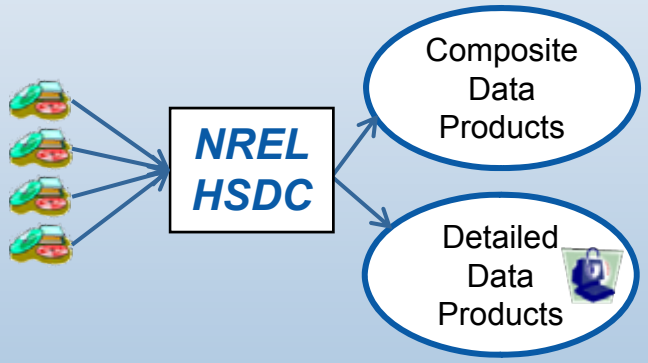
All 1st generation vehicles deployed
2nd generation introduction Fall '07

FC Degradation Analysis

- ***Objectives***
  - Learn if there are **observable relationships** between the FCV Learning Demonstration **real world data** (driving and filling) and **fuel cell degradation**.
  - Include fuel cell design and driving tendency factors
  - Report on dominant factors (if there are any) affecting fuel cell degradation

Note: data not specifically controlled for a FC degradation study.

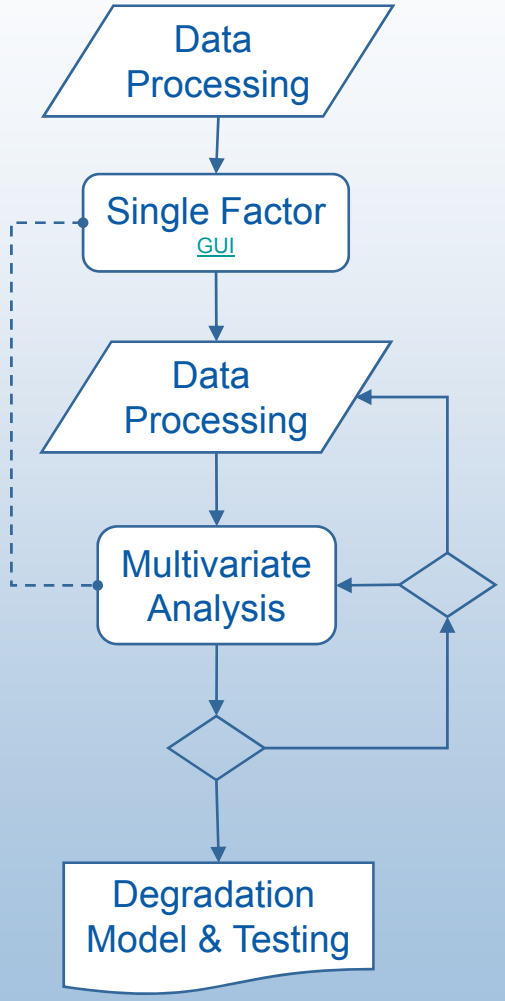




Through August 2007:
- >149,000 individual vehicle trips
- 40 GB of on-road data
- >2 yrs data analyzed
- >2 yrs of data to gather

Multivariate Analysis Overview

- Why multivariate analysis?
  - Uncontrolled degradation experiment
  - Likely a combination of factors in real world applications
  - A dominant single factor not apparent from Single Factor analysis step
  - Reduction of factors
- Why Partial Least Squares (PLS)?
  - Concentration on observation, FC decay rate
  - Latent Variables (LVs) assembled to explain maximum decay rate variance



Data Pre-Processing

- FC operation trip filters
- Sample (FC) filter
- Factors
  - FCV Learning Demonstration, Gen I available data.
  - Factors may vary between project partners.
  - Factor examples
    - Trip detail factors
    - Fuel cell performance factors
- Scaled & mean-centered data
- Data through September 2007
- Observation: FC Decay Rate
  - Voltage decay estimate
  - Low, average, or high decay rate classification

Data Set

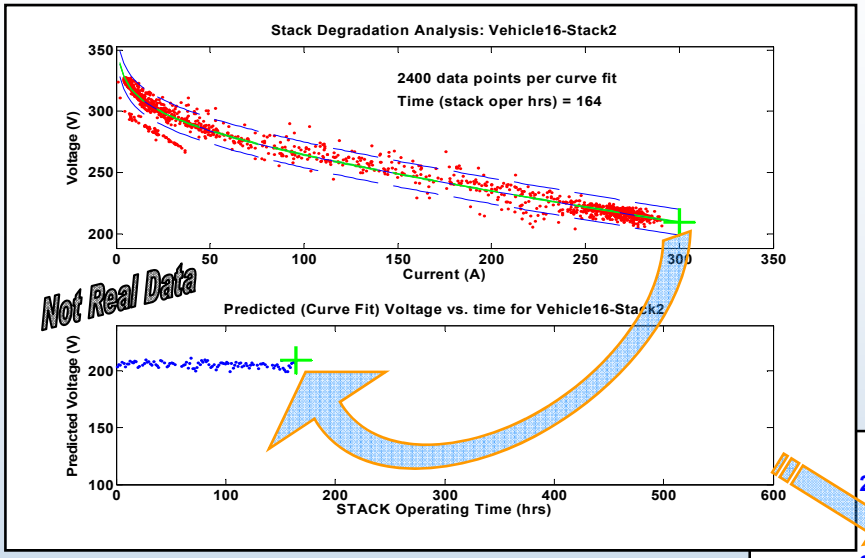
Variable Categories

FC Power
Install Date
Starts/hr
Idle Time
Initial Condition
Time Between Trips
Trip Length
Ambient Trip Temperature
Filling Station H2 production method
# of 0 speed trips
Voltage
Current
Successful FC starts

Sample	*Decay Rate*	*Variables*			
Stack1	DR1	Data(1,1)	Data(1,2)	…	Data(1,75)
Stack2	DR2	Data(2,1)	Data(2,2)	…	Data(2,75)
.	.	.	.		.
.	.	.	.		.
.	.	.	.		.
.	.	.	.		.
Stack31	DR31	Data(31,1)	Data(31,2)	…	Data(31,75)

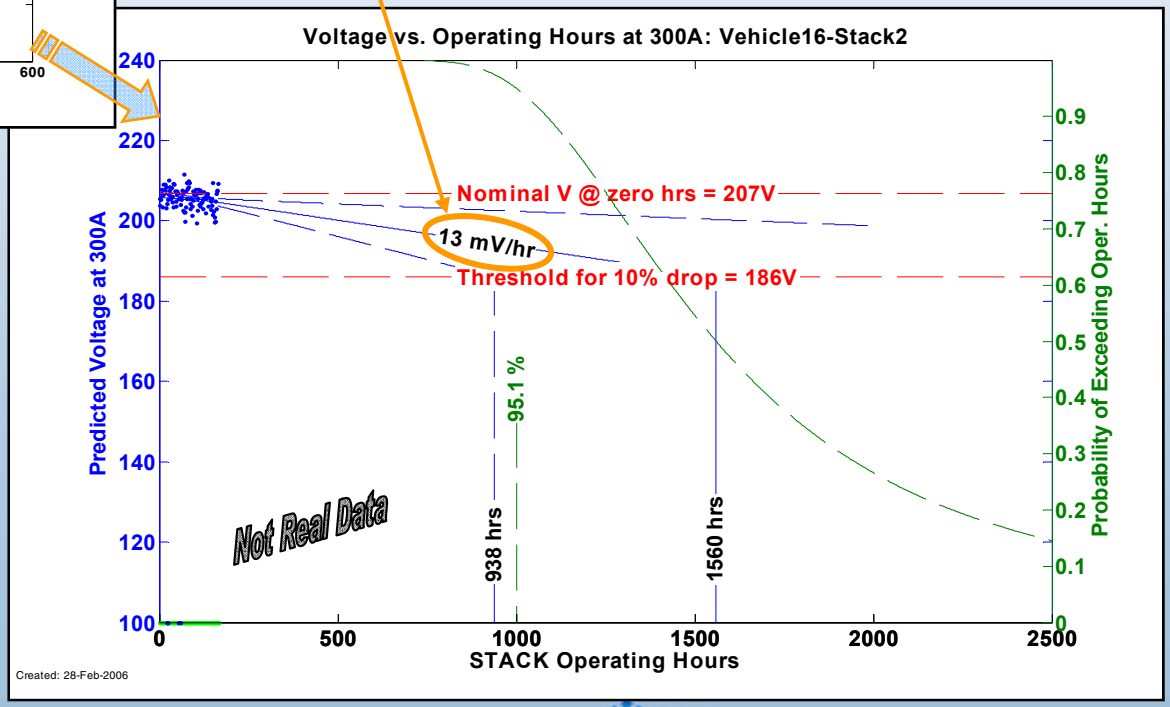
Simulated Data Set Example

Method for Projecting Time to 10% Fuel Cell Stack Voltage Degradation



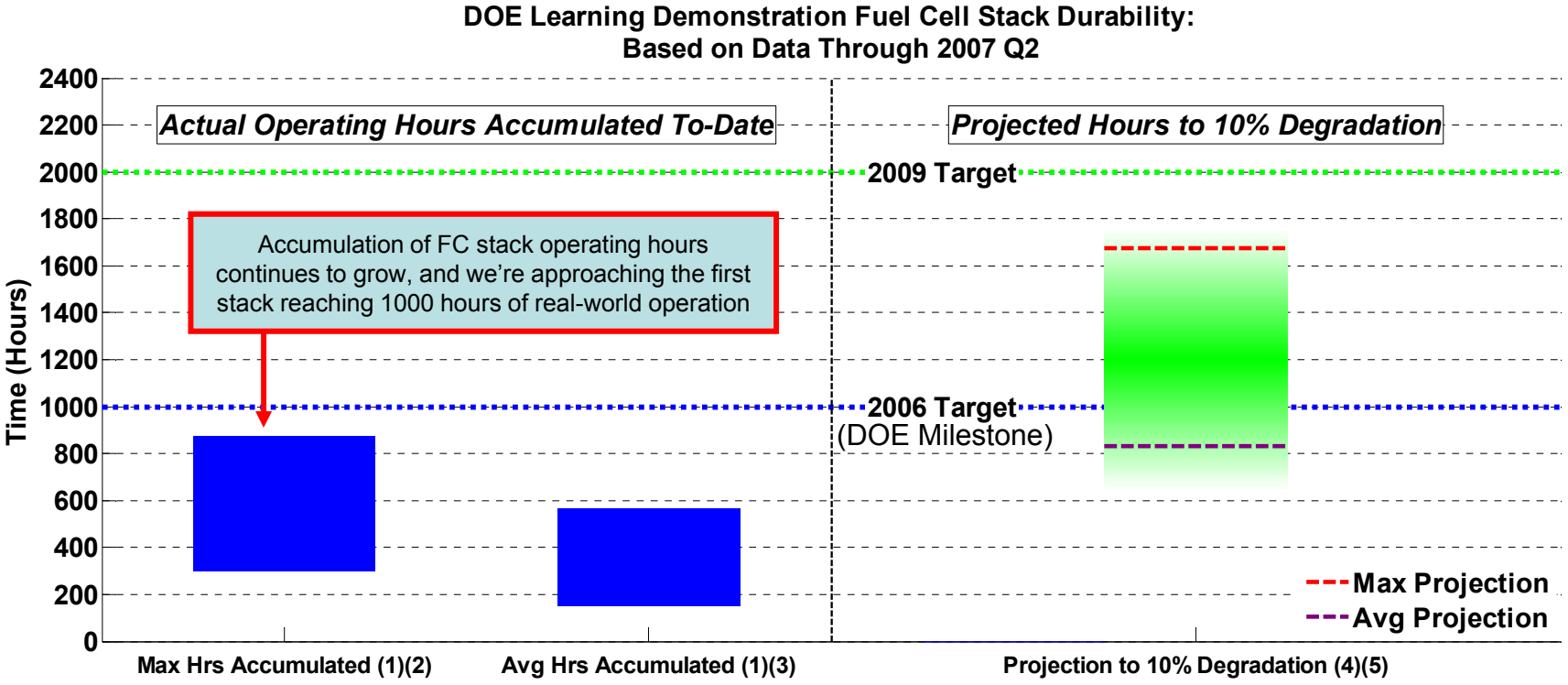
Note: a 10% decay in operating voltage is a DOE **benchmark**, ***not*** an indication of fuel cell end-of-life.

Decay rate = slope of fit line



Technique makes performance projection based on all available FC data & includes confidence intervals.

As More Gen 1 Data Is Accumulated, Some Teams Are Demonstrating Long FC Durability

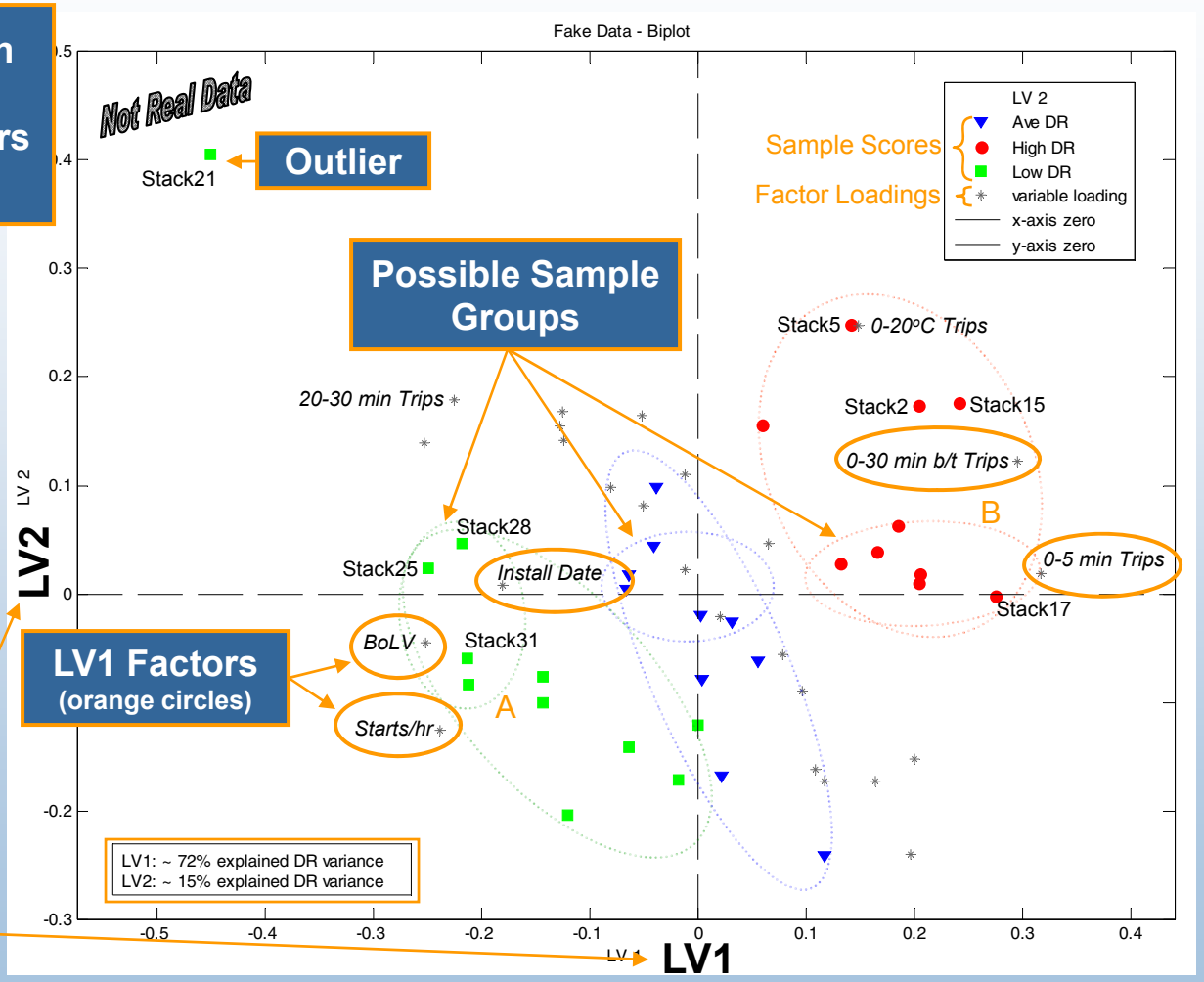


(1) Range bars created using one data point for each OEM.
(2) Range (highest and lowest) of the maximum operating hours accumulated to-date of any OEM's individual stack in "real-world" operation.
(3) Range (highest and lowest) of the average operating hours accumulated to-date of all stacks in each OEM's fleet.
(4) Projection using on-road data -- degradation calculated at high stack current. This criterion is used for assessing progress against DOE targets, may differ from OEM's end-of-life criterion, and does not address "catastrophic" failure modes, such as membrane failure.
(5) Using one nominal projection per OEM: "Max Projection" = highest nominal projection, "Avg Projection" = average nominal projection. The shaded green bar represents an engineering judgment of the uncertainty due to data and methodology limitations. Projections will change as additional data are accumulated.

Created: Aug-23-07 10:42 AM

What are the Correlations?
BiPlot Example

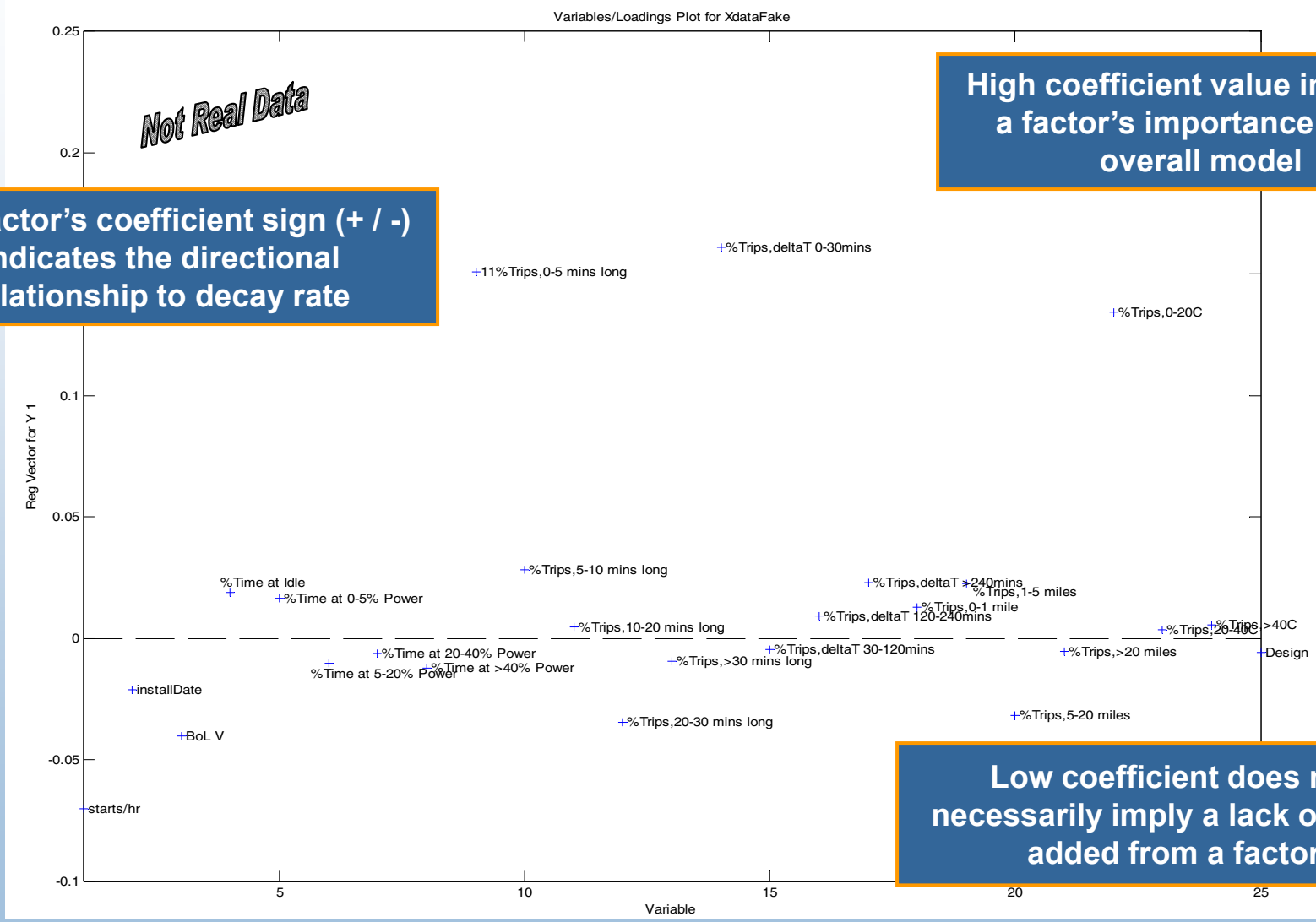
Goal: find tendencies within the decay rate groups that translate to decay rate factors and the factors' affects



Latent Variables: Combination of input factors that describe decay rate variance

Note: the data depicted here helps illustrate the process for the Learning Demonstration (LD) analyses. Ultimately, the goal is to identify factors of decay rate and what the affect is (positive or negative). In order to do this, tendencies within the low, average, and high decay rate classification need to apparent. The actual data is more scattered than the example shown here, thus making it more difficult to identify patterns, especially in the LD fleet analysis.

What Factors are Important to the Model?
Regression Vector Example

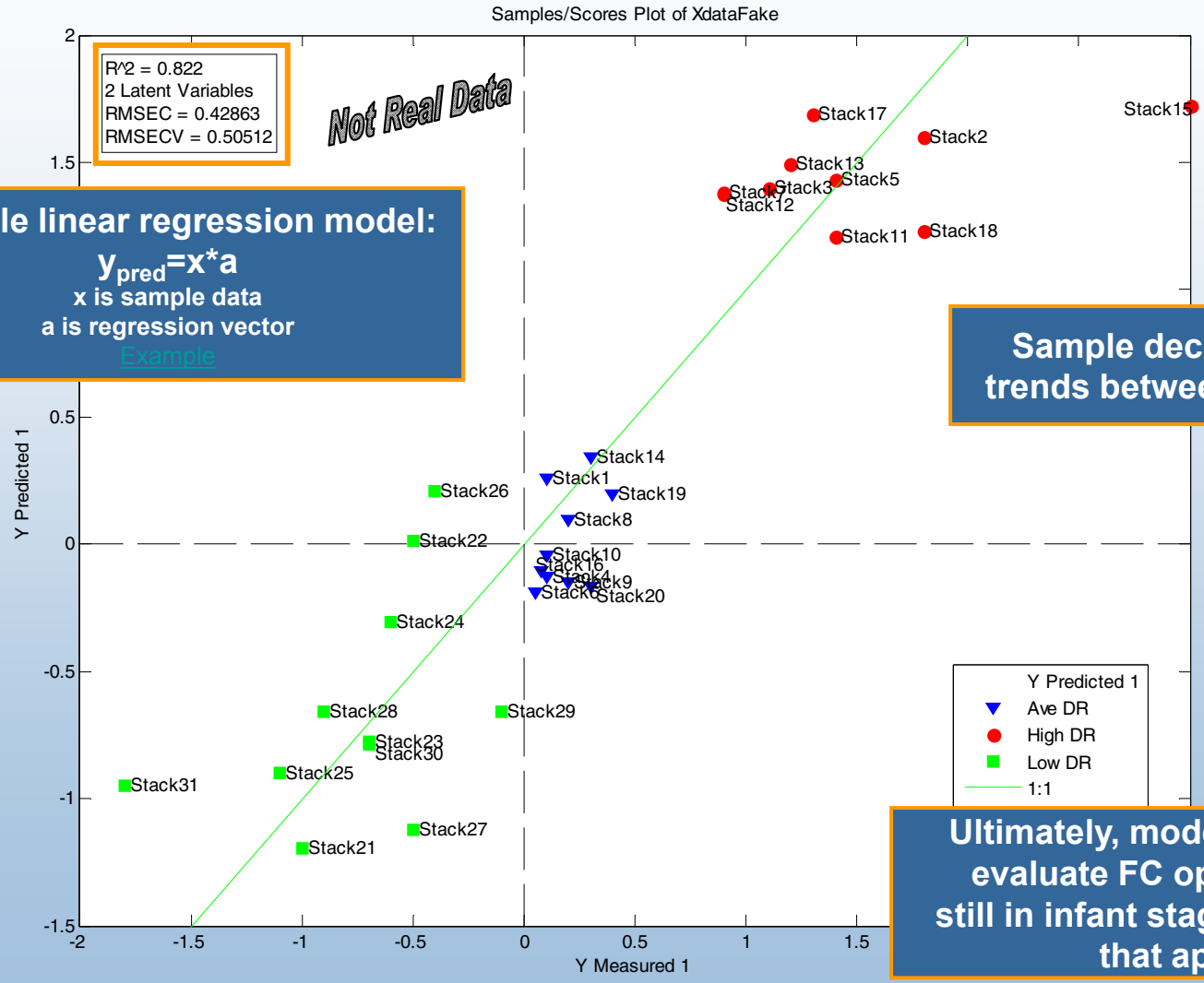


High coefficient value indicates a factor's importance in the overall model

The factor's coefficient sign (+ / -) indicates the directional relationship to decay rate

Low coefficient does not necessarily imply a lack of value added from a factor

How Good is the Model?
Predicted vs. Measured Example



Multiple linear regression model:

$y_{pred}=x*a$

x is sample data

a is regression vector

Example

Sample decay rate prediction & trends between decay rate classes

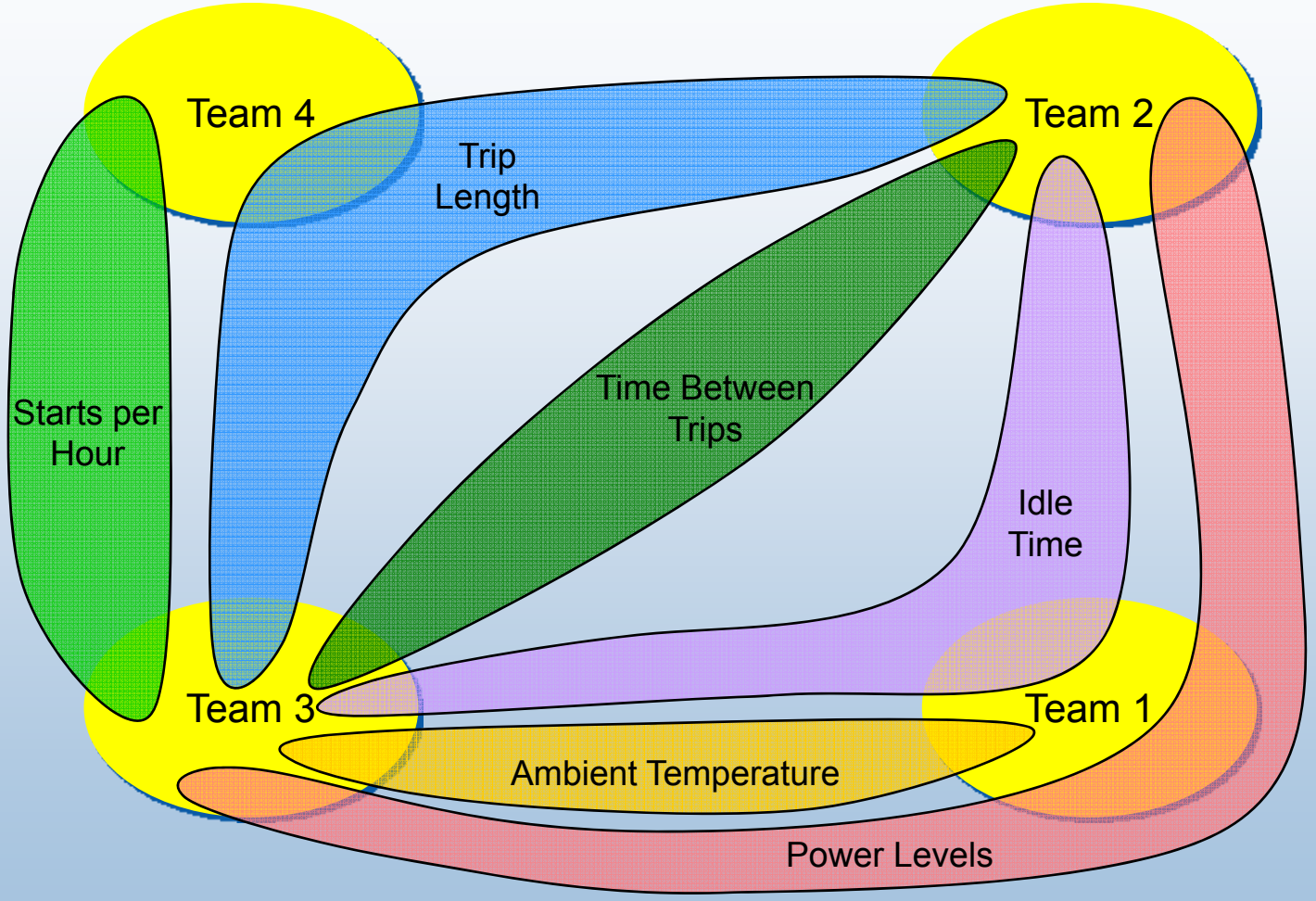
Ultimately, model could be used to evaluate FC operation changes; still in infant stage and not ready for that application.

PLS Results - Learning Demonstration Degradation Factor Summary

~29% Decay rate variance explained by a combination of the data variables below[1]	***Correlation to Decay Rate Data***
Starts per hour (+)	High decay rate[2]
Power levels (high & average) (+)	
Trip length (-)	
Time between trips (+)	
~10% Decay rate variance explained by a combination of the data variables below[1]	***Correlation to Decay Rate Data***
Idle time (+)	High decay rate[2]
Power levels (low) (+)	

1. Findings based on a Learning Demonstration Fleet, Partial Least Squares (PLS) regression model. Approximately 39% decay rate variance explained by the model.
2. As part of the variable combination, a (+) indicates a directional relation to high decay rate and a (-) indicates an inverse relation.

PLS Results – Identification of Factors Contributing to FC Degradation per Team



1. Results are from partial least squares (PLS) regression analysis of each team's fleet of vehicles individually
2. First two collections of factors cover ~61%-76% of decay rate variance

Created: Aug-31-07 9:00 AM

Summary

- Gen I FCV on-road data (77 vehicles)
- Different look than a lab study of degradation
- Analysis Learning
  - Adjustment of input factors & included samples
  - Correlation and interpretations
  - Decay rate classifications
  - Analysis iterations & variations
  - Additional data
- Complex factor interactions affecting FC degradation
- Team level analysis vs. DOE Fleet level analysis
  - Team level analysis more valuable because of the variations between teams
  - Team level analyses high R^2, but not robust
  - Identification of trends difficult because of scattered sample data
  - Use DOE Fleet level analysis to compare difference between teams
- **Collaboration** with teams

Contact Information

Jennifer Kurtz

National Renewable Energy Laboratory

jennifer_kurtz@nrel.gov

303-275-4061

Keith Wipke (Primary project contact)

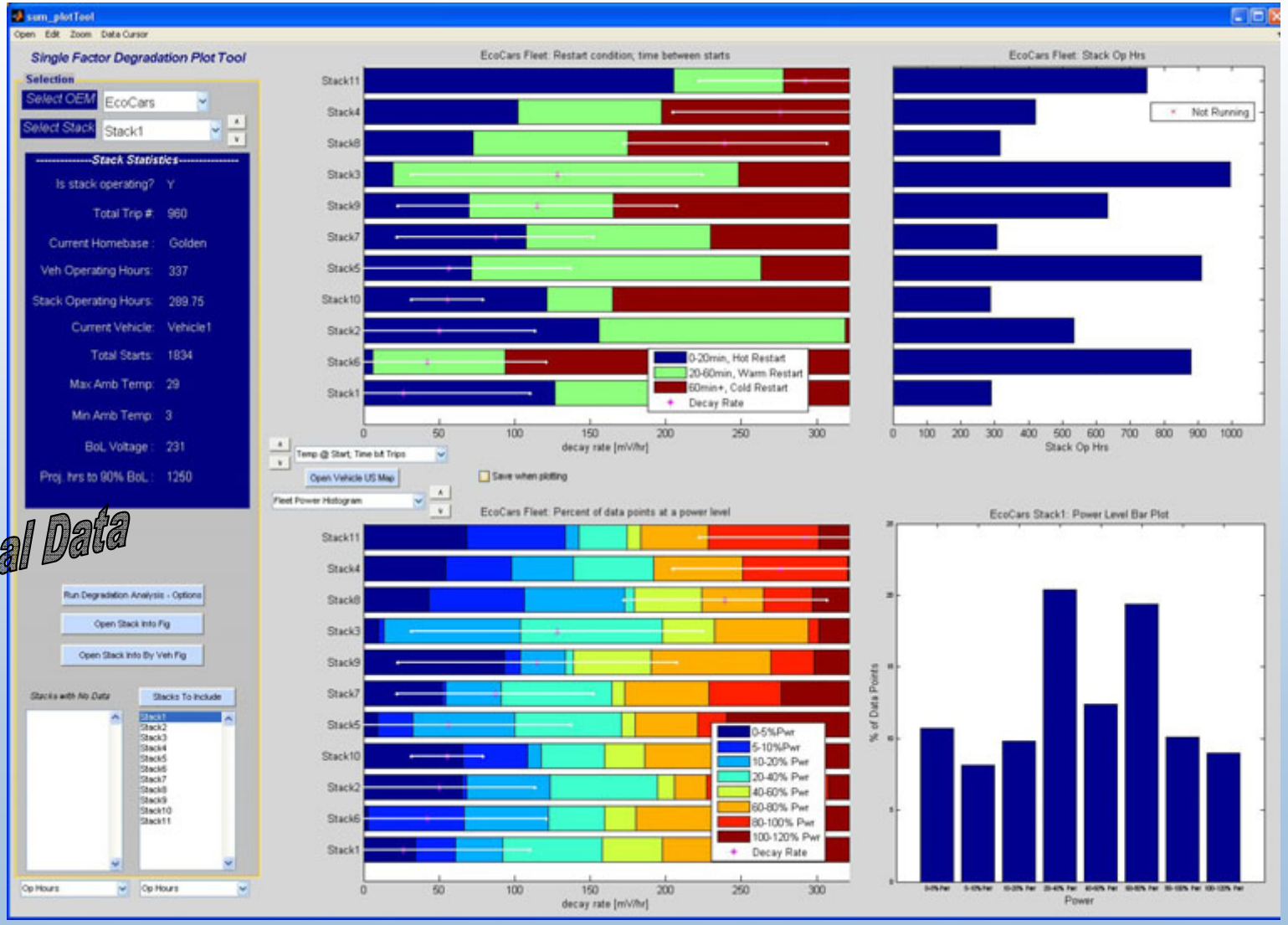
National Renewable Energy Laboratory

keith_wipke@nrel.gov

303-275-4451

All public Learning Demo papers and presentations are available online at http://www.nrel.gov/hydrogen/proj_tech_validation.html

Single Factor GUI



NREL Web Page Provides Direct Access to All Composite Data Products

http://www.nrel.gov/hydrogen/cdp_topic.html

NREL : Hydrogen and Fuel Cells Research - Composite Data Products by Topic - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Address http://www.nrel.gov/hydrogen/cdp_topic.html

NREL National Renewable Energy Laboratory

Innovation for Ou

ABOUT NREL | SCIENCE & TECHNOLOGY | TECHNOLOGY TRANSFER | APPLYING TECHNOLOGIES | LEARNING ABOUT RENEWABLES

Hydrogen & Fuel Cells Research

- Hydrogen Research Home
- Capabilities
- Projects
  - Hydrogen Production & Delivery
  - Hydrogen Storage
  - Fuel Cells
  - Technology Validation
  - Fuel Cell Vehicle Learning Demonstration
  - Fuel Cell Bus Evaluations
  - Safety
  - Codes & Standards
  - Analysis
  - Education
- Research Staff
- Working with Us
- Partnerships
- Energy Analysis & Tools
- Publications
- Awards

View the Learning Demonstration CDPs:

- By topic
- By date
- By CDP#

Composite Data Products by Topic

The public technical analysis results from DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project are generated in the form of composite data products (CDPs). The following CDPs, which are organized by topic, are offered in both PowerPoint and JPEG formats.

If these technical results are reproduced in your own documents or presentations, please provide appropriate reference to the U.S. Department of Energy's National Renewable Energy Laboratory.

Fuel Cell Stack Durability

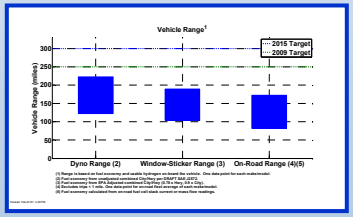
- Learning Demo Fuel Cell Stack Hours Accumulated, CDP #1A, 2/28/07 (PowerPoint 388 KB) (JPEG 89 KB)
- Projected Hours to 10% Stack Voltage Degradation, CDP #1B, 2/28/07 (PowerPoint 391 KB) (JPEG 155 KB)
- Fuel Cell Stack Hours Accumulated and Projected Hours to 10% Stack Voltage Degradation, CDP #1C, 2/28/07 (PowerPoint 392 KB) (JPEG 169 KB)

Fuel Cell Vehicle Range

- Fuel Cell Vehicle Range, CDP #2, 2/27/07 (PowerPoint 389 KB) (JPEG 121 KB)
- Effective Fuel Cell Vehicle Range, CDP #34, 2/26/07 (PowerPoint 389 KB) (JPEG 78 KB)
- Percentage of Theoretical Driving Range Between Refuelings, CDP #33, 2/26/07 (PowerPoint 392 KB) (JPEG 97 KB)

Fuel Cell Vehicle Fuel Economy and Stack Efficiency

- Fuel Cell Vehicle Fuel Economy, CDP #6, 2/27/07 (PowerPoint 388 KB) (JPEG 102 KB)
- Fuel Cell System Efficiency, CDP #8, 8/29/06 (PowerPoint 392 KB) (JPEG 97 KB)



Trusted sites

Equation Example

The model equation is:

$$y_{pred}=x*a+b,$$

where a is the regression vector, x is a sample's data vector, y_{pred} is the predicted decay rate, and b is the intercept (b=0 for this model).

Because of the data processing (mean-centering and scaling) in the model, the x & y_{pred} value is processed and y_{pred} is reverted back into decay rate units for the prediction.

x=sample data, a vector that is 1 by factor #:

e.g. [50 300 .5 ……. .7 .2 1]

a = regression vector, a vector that is factor # by 1:

e.g. [.4 .1 -.3 …… .1 -.1 .1]'

Simulated Data Set Snapshot

Scaled & mean-centered Simulated Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1		dr class	decay rate	'starts/hr'	'installDate'	'BoL V'	'%Time at Idle'	'%Time at 0-5% Power'	'%Time at 5-20% Power'	'%Time at 20-40% Power'	'%Time at >40% Power'	'11%Trips ,0-5 mins long'	'%Trips,5-10 mins long'	'%Trips,10-20 mins long'	'%Trips,20-30 mins long'	'%Trips,>30 mins long'	'%Trips,deltaT 0-30mins'	'%Trips,deltaT 30-120mins'	'%Trips,deltaT 120-240mins'	'%Trips,deltaT >240mins'
2	'Stack1'	'Ave DR'	0.1	-0.1224	-0.0433	-0.2671	0.9801	2.0946	-1.097	-1.3893	-0.4951	0.2587	-1.3046	0.9192	-0.284	0.0594	0.988	0.029	-0.9523	1.9088
3	'Stack14'	'Ave DR'	0.3	0.9564	0.1621	-1.7865	1.1668	-0.3718	3.3533	-2.3877	-2.0153	1.5372	-0.5175	-0.946	-0.7902	-0.2794	0.6148	0.1669	0.6087	-0.0901
4	'Stack19'	'Ave DR'	0.4	-2.6699	1.8057	-0.0359	-1.1829	-0.8934	-0.7473	2.4426	0.2698	-1.4345	-0.0127	-0.1324	1.241	1.1452	2.6778	1.8368	0.415	0.315
5	'Stack4'	'Ave DR'	0.1	-0.6632	0.796	-1.3993	-0.925	0.6467	-0.7417	0.1277	-0.0823	-1.2796	-0.2806	0.1573	1.1257	0.9811	0.2081	-2.1949	1.1156	0.8852
6	'Stack16'	'Ave DR'	0.08	-1.8554	1.9325	1.9854	0.2644	0.1928	-0.6638	-0.1239	0.7469	0.0567	1.5482	0.552	-0.6348	-1.269	-1.1313	-0.2027	0.7208	-0.774
7	'Stack6'	'Ave DR'	0.05	-0.1575	-0.9132	-0.7291	0.216	0.6075	-0.1523	0.5761	-1.2568	-0.5223	0.1478	1.3778	0.5948	-0.9698	-1.1713	-0.112	0.3438	0.2379
8	'Stack20'	'Ave DR'	0.3	0.3114	1.3161	0.4388	-0.3527	1.7141	-1.6304	-0.6724	0.2142	0.2595	-0.6156	0.355	0.466	-0.4677	-0.8561	-0.3481	0.7648	-0.3795
9	'Stack8'	'Ave DR'	0.2	-0.0802	-1.5164	-0.5007	-0.3233	0.7031	-0.3645	-0.2415	-0.3731	0.0027	-0.9539	-0.6931	-0.4886	1.5929	0.3993	-2.0619	-0.3436	0.7792
10	'Stack9'	'Ave DR'	0.2	2.272	-1.2803	-0.8049	0.9042	-0.1033	0.2058	0.2714	-0.3721	0.8292	0.5067	-0.6316	-0.1037	-0.8406	-0.8424	-0.3043	0.0551	-0.6103
11	'Stack10'	'Ave DR'	0.1	0.3512	-1.088	-0.4266	1.0646	-2.1375	1.2576	1.1686	0.5334	0.3913	-0.9348	1.1198	-0.1601	-0.6294	0.2247	0.9886	-0.0973	-0.1242
12	'Stack7'	'High DR'	0.9	0.0434	-0.97	0.1327	0.0971	-0.2427	0.2325	0.5559	-0.446	3	0.1987	0.0147	0.2737	-0.4188	3	-1.0885	0.117	0.2037
13	'Stack12'	'High DR'	0.9	-1.0645	-1.1929	-1.1501	-0.0091	-1.6408	0.4643	1.702	0.3959	3.2	-1.7495	-0.3418	1.3338	0.2672	3.2	0.0573	0.0822	1.1605
14	'Stack13'	'High DR'	1.2	1.3481	-0.1176	1.4045	1.3163	0.3012	0.9483	-1.0956	-0.8314	3.3	1.8198	-1.1097	-0.8793	-1.1554	3.3	0.3438	-0.2039	-0.0355
15	'Stack5'	'High DR'	1.4	-0.338	0.7697	-0.4182	-0.3149	1.5561	-1.1299	-0.6303	-0.2813	3	-0.9433	1.3992	0.1117	0.8583	3	-0.6045	0.6944	-0.1321
16	'Stack15'	'High DR'	3	-0.3652	-0.97	0.0042	0.3699	1.0604	-0.822	-0.8	0.2131	3.4	0.0037	0.3136	-0.9103	0.1576	3.4	-0.2978	0.3685	0.3322
17	'Stack2'	'High DR'	1.8	-0.1616	-0.97	0.0787	-0.498	0.4472	-0.0605	-0.1787	-0.4572	3.3	2.474	-0.8301	-0.3182	-0.049	3.3	0.2543	-0.8566	-0.2694
18	'Stack17'	'High DR'	1.3	0.0157	0.6867	-1.0452	-2.0373	-0.3112	1.0023	-0.1477	-0.7956	3.4	0.9652	-2.931	-2.0341	0.9453	3.4	1.5767	2.4232	0.3374
19	'Stack18'	'High DR'	1.8	0.4296	-0.3012	0.9709	0.8241	-1.0083	0.333	0.9692	0.2446	3	-0.2315	0.7668	-0.1687	-1.0141	3	-0.5258	-0.5702	0.0873
20	'Stack11'	'High DR'	1.4	0.6729	1.8538	1.3549	0.4893	-0.6673	-0.0349	0.9572	0.2396	3.2	-0.6295	1.9543	-0.1645	-0.6314	3.2	0.7293	-1.2537	0.0526
21	'Stack3'	'High DR'	1.1	1.6345	-0.0214	-0.2185	0.9666	-1.0085	0.6782	-0.1478	0.7591	3.1	1.3455	-0.6422	-1.3496	-1.2967	3.1	-0.503	-0.1216	0.1326
22	'Stack21'	'Low DR'	-1	5	0.8	3	-3.0161	-0.9376	-1.0309	-0.956	3.7897	-3.0329	-0.836	-0.6717	3.1392	3.0144	-1.6469	2.2609	-3.3098	-4.0173
23	'Stack22'	'Low DR'	-0.5	4	0.9	3.2	-1.1538	-1.3636	-1.3915	2.492	1.1191	2.2425	-0.0733	-1.6059	-2.0713	-0.8754	0.0138	-1.9133	0.5153	-0.2824
24	'Stack23'	'Low DR'	-0.7	8	1	3.3	0.1678	-0.2314	-1.0224	1.0162	0.1064	0.365	1.9118	-0.8217	-0.9249	-0.1906	-0.7116	0.1544	1.1529	-0.3456
25	'Stack24'	'Low DR'	-0.6	6	1	3	-1.1478	-0.8106	-0.7513	1.065	1.0974	1.3586	-0.0588	-1.4506	-0.7715	-0.4371	0.8418	2.4091	1.8478	1.2701
26	'Stack25'	'Low DR'	-1.1	5	1	3.4	-0.8019	0.1015	0.197	0.0506	-0.4357	-0.4387	-1.2337	2.0068	2.2285	-1.2642	-1.3634	-0.8135	-2.0669	-1.9613
27	'Stack26'	'Low DR'	-0.4	4	0.9	3.3	2.3868	0.2159	-1.2385	-0.0499	0.5612	1.6762	0.0591	-1.2721	-1.3218	-0.8226	-0.8337	-1.27	0.1027	-0.0975
28	'Stack27'	'Low DR'	-0.5	8	0.8	3.4	1.0144	1.5754	-1.0684	-1.2042	-1.1699	-1.1214	-0.0688	0.0221	0.1769	1.4007	-1.0636	-0.029	-0.3601	0.1698
29	'Stack28'	'Low DR'	-0.9	6	1	3.2	-0.5118	-0.5713	0.2357	0.0055	0.9582	0.039	-0.7643	0.392	1.1355	-0.5296	-1.1349	0.6159	-1.1922	-1.6271
30	'Stack29'	'Low DR'	-0.1	8	0.8	3.1	1.4142	2.194	-1.4426	-1.5923	-1.7649	-0.9529	0.73	-0.4633	-0.295	1.4613	0.6977	-1.4262	-0.4134	0.9107
31	'Stack30'	'Low DR'	-0.7	7	1	3.4	-0.9981	-1.4434	1.8432	0.0257	0.7211	-0.8587	2.3917	1.2358	0.6589	-0.7507	0.1136	0.6887	0.347	0.7259
32	'Stack31'	'Low DR'	-1.8	6	1	3.2	0.3995	0.8812	0.89	-1.1677	-1.2388	-1.176	-1.2937	0.1155	1.0806	1.4299	-0.1617	-0.4517	-0.1695	-0.4993